



Advances in antimonide-based Type-II superlattices for infrared detection and imaging at center for quantum devices



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HIGHLIGHTS

- ▶ InAs/GaSb T2SLs are now strong candidates for next generation of IR imagers.
- ▶ This material system covers the whole infrared spectrum from SWIR to VLWIR.
- ▶ High operating temperature and mega-pixel focal plane arrays have been achieved.
- ▶ Growth on alternative substrates has been successfully done.
- ▶ State-of-the-art multi-spectral infrared photodetectors and imagers are presented.

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ABSTRACT

Type-II InAs/GaSb superlattices (T2SLs), a system of multi-interacting quantum wells, was introduced by Nobel Laureate L. Esaki in the 1970s. Since then, this material system has drawn a lot of attention especially for infrared detection. In recent years, T2SL material system has experienced incredible improvements in material quality, device structure designs and device fabrication process which elevated the performances of T2SL-based photo-detectors to a comparable level to the state-of-the-art material systems for infrared detection such as Mercury Cadmium Telluride (MCT). In this paper, we will present the current status of T2SL-based photo-detectors and focal plane arrays for imaging in different infrared regions, from SWIR to VLWIR, and the future outlook of this material system.

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1. Introduction

The idea of Type-II InAs/GaSb superlattice (T2SL) was first proposed by Sai-Halasaz and Esaki in the 1970s [1]. The superlattice is formed by alternating the InAs and GaSb layers over several periods. The Type-II broken gap alignment leads to the separation of electrons and holes into the InAs and GaSb layers, respectively. The charge transfer gives rise to a high local electric field and strong interlayer tunneling of carriers without the requirement of an external bias or additional doping. Large period superlattices behave like semimetals but if the superlattice period is shortened, the quantization effects are enhanced causing a transition from a semi-metal to a narrow gap semiconductor. The resulting energy gaps depend upon the layer thicknesses and interface compositions.

T2SL has several advantages over other materials used for infrared detection and imaging technologies [2]. Compared to state-of-the-art Mercury Cadmium Telluride (MCT) and most of

the small band gap semiconductors that have very small electron and hole effective masses, the effective mass in T2SLs is relatively large, due to its special design which involves the interaction of electrons and holes via tunneling through adjacent barriers. Larger effective mass reduces the tunneling current, which is a major contributor to the dark current of long- and very long wavelength MCT detectors. Moreover, Auger recombination, which is a limiting factor for high temperature operation of infrared detectors, can be suppressed by manipulation of the energy band structures [3]. The capability of band structure engineering opens the horizon for exploring novel device architectures that are unthinkable using simple binary or ternary compound semiconductor band alignments like MCT. As an example, recent research has proposed a novel variant of T2SL, the M-structure superlattice (SL), with large effective mass and large tunability of band edge energies [4]. The structure has been shown to efficiently reduce the dark current in photovoltaic detectors. Due to all these fundamental properties, T2SL has experienced a rapid development over the past decade and its performance has reached a comparable level with the state of the art MCT detectors. In this paper, we will discuss the current

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status of the state-of-the-art Type II superlattice photo-detectors and focal plane arrays and the outlook for this material system.

2. Photodiodes and focal plane arrays from short- to very long-wavelength infrared

2.1. Short-wavelength infrared photo-detectors

The main challenge for short-wavelength infrared (SWIR) detection is the proper Type-II superlattice design. Using InAs/GaSb T2SL, the large bandgap requires a thin InAs layer to push up the conduction band. The forced InSb interface will therefore result in lattice mismatch and prevent us from growing thick structure. Ternary $\text{Ga}_x\text{In}_{1-x}\text{Sb}$ interface or GaAs interface have been used to address the problem. However, these techniques have still only been used in mid-wavelength infrared (MWIR) regime and the shortest cut-off wavelength is expected to be around 3 μm . From the great tunability of the M-structure SLs, a new superlattice design matched to GaSb substrate was proposed and experimentally demonstrate the SWIR detection [5]. By reducing the InAs and GaSb layer thicknesses and using a thick AlSb layer, we have been able to create high quality T2SL capable of SWIR detection. As shown in Fig. 1 (left), due to its high carrier effective mass and high energy band gap, the AlSb layer plays a significant role in changing the band structure of both conduction band and valence band, resulting in a high band gap for SWIR absorption. Different superlattice designs as SWIR absorption layer were proposed. Their bandgap was calculated using the empirical tight binding modeling (ETBM) [6] as shown in Fig. 1 (right). With guaranteed lattice match condition, these M-structure SLs would be able to theoretically aim for shorter cut-off wavelengths as short as 1.5 μm .

A typical T2SL-based SWIR device consisted of 0.5 μm thick bottom n-contact ($n \sim 10^{18} \text{ cm}^{-3}$), 2 μm thick undoped active region and 0.5 μm thick top p-contact ($p \sim 10^{18} \text{ cm}^{-3}$). The structural characterization with AFM and X-ray exhibited an excellent morphology with small roughness of 1.12 $\text{\AA}$ over a $5 \times 5 \mu\text{m}^2$ area and high ordered diffraction peaks with full width at half maximum at zero order was ~ 44 arcsec. The mismatch between the SL and the GaSb substrate was only 480 ppm, which was fitted well with our calculation and thus far from harming the crystallinity of the material.

At 150 K, the photodiodes exhibited a dark current density of $5.6 \times 10^{-8} \text{ A/cm}^2$ and a quantum efficiency of 40.3% at front-side illumination configuration, resulting in an associated shot noise detectivity of 1.0×10^{13} Jones. At room temperature, photodiodes

demonstrated a dark current density of $2.2 \times 10^{-3} \text{ A/cm}^2$ and a quantum efficiency of 41.5% (Fig. 2). This work has further extended the detection range of T2SL to cover from SWIR to very long-wavelength infrared (VLWIR) and open the possibility of incorporating active and passive imaging in a T2SL-based focal plane array (FPA).

2.2. Mid-wavelength infrared photo-detectors and focal plane arrays

The detection of electromagnetic waves at the atmospheric transparent window between 3 and 5 μm , usually referred to as mid-wave infrared (MWIR), can be utilized for many applications such as aerial and satellite reconnaissance, target tracking using heat signals, navigation and object identification. Similarly to the SWIR T2SL devices, the first challenge in realizing the MWIR photo-detectors is the superlattice design for the absorption region. Two InSb interfaces caused high mismatch when a thin InAs layer is used. By using highly controllable ternary interface $\text{Ga}_x\text{In}_{1-x}\text{Sb}$, high quality material lattice matched to GaSb substrate was achieved for the MWIR detection to 3.7 μm . The device structure also witnessed a lot of progress. From the standard p-i-n homo-junction device structure, a various number of hetero-structure structures like p- π -M-n and pMp were proposed to improve the optical and electrical performance thanks to the flexibility in band gap engineering.

The first objective in this study is to increase the operating temperature ($>150 \text{ K}$) of MWIR T2SL photo-detectors which allows us to operate them without a burden cryogenic system. The obstacles in realizing high operating temperature (HOT) for direct bandgap semiconductors are the exponential increase in the minority carrier concentration versus temperature as well as the reduction in the carrier lifetime as a result of Auger recombination at high temperatures.

In order to tackle this problem, a novel device structure, called p- π -M-n, was designed and fabricated by inserting an M-structure tunneling barrier into the junction of MWIR T2SL photodiodes [7]. M-structure superlattice with good band alignment in the conduction band with the active region was used to block the tunneling current while having no bias dependency of quantum efficiency. With the larger barrier potential and larger electron effective mass, the M-structure effectively suppressed the tunneling current without affecting the photocurrent (Fig. 3).

Suppression of the tunneling allowed us to increase the doping level of the active region to suppress the diffusion current. Higher doping level in active region leads to a smaller number of minority

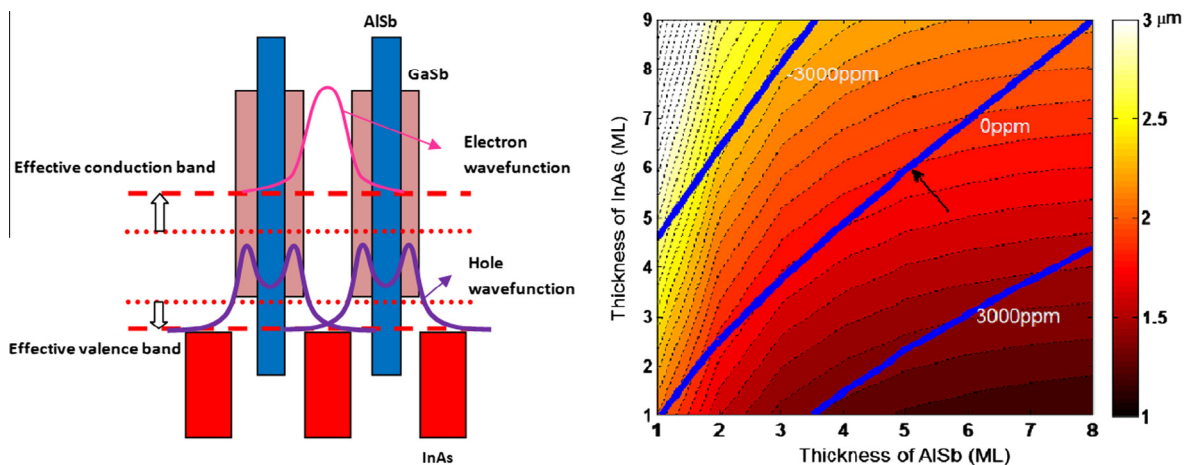


Fig. 1. (Left) M-structure superlattice and the creation of effective band gap. Colored rectangles represent the prohibited band gap of the materials. (Right) Calculated map of 50% cutoff wavelengths for the superlattice of $(\text{InAs})_n\text{-GaSb-(AlSb)}_m\text{-GaSb}$ as function of InAs and AlSb layer thickness (number of monolayers). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

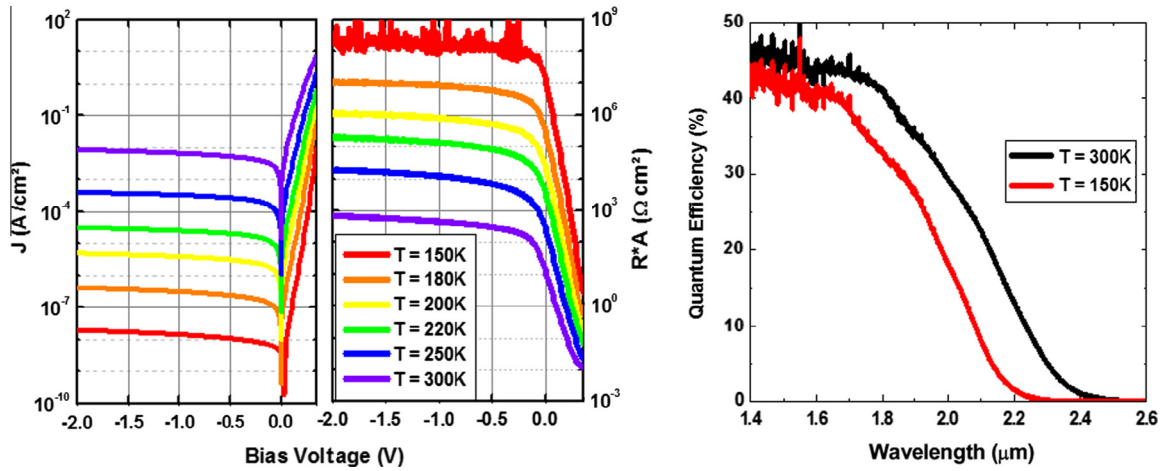


Fig. 2. (left) dark current density and differential resistance $\times$ area of a T2SL SWIR photodiode as a function of temperatures. (right) Quantum efficiency the same photodiode at 150 K and 300 K.

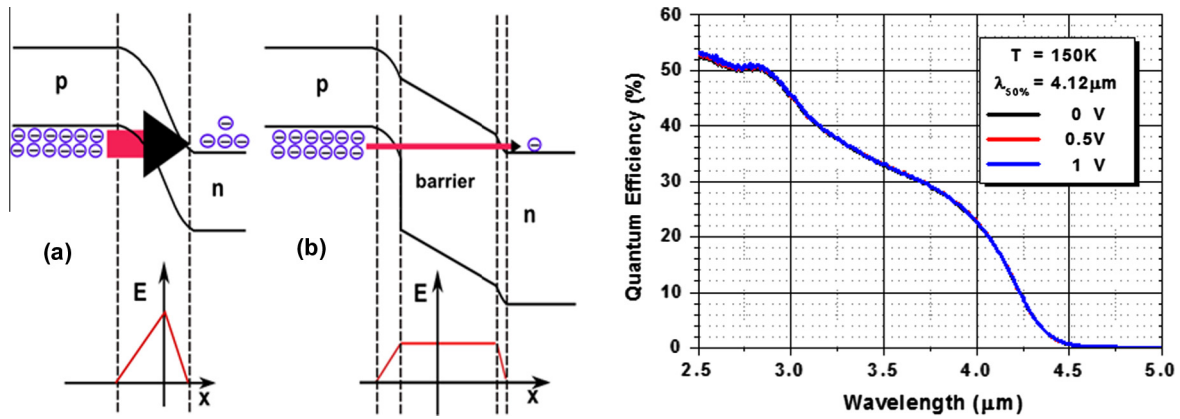


Fig. 3. (left) Effect of M-barrier in suppressing the tunneling current in MWIR photodiodes while fully extracting (right) quantum efficiency without bias dependence.

carriers which are the source of diffusion component in the dark current. The electrical performance of the detectors was improved by a factor of 4 just by increasing the doping level while more than an order of magnitude improvement was observed with the combination of the barrier and the doping level.

The improvement in the R_0A is obvious in the whole temperature range of interest from 120 to 230 K. At operating temperatures higher than 200 K the three values start to converge since the active region starts to become intrinsic and the diffusion current does not depend on the doping level anymore. At low temperature, the dominant mechanism starts to become generation–recombination (G–R) or tunneling which is not a strong function of the doping level, but mostly depends on the density of deep level traps inside the bandgap. This causes the convergence of the three curves at low temperatures. Fig. 4 (right) presents the specific detectivity (D^*) spectrum of the sample with the highest doping and best performance at different temperatures with respect to the BLIP line. The devices demonstrate a R_0A of 5100 Ω cm² and a specific detectivity of 1.05×10^{12} Jones at 150 K. They were BLIP up to 180 K assuming 100% quantum efficiency, 300 K background, and 2 π field-of-view (FOV).

Another alternative for MWIR regime is pMp device structure [8]. The first pMp device concept was initially demonstrated in the VLWIR regime. Taking advantage of the unipolar minority carrier photo-detectors with no p–n junction, the pMp design was expected to reduce the dark current due to tunneling and G–R. The simplicity of design is also useful in multi-band detection. MWIR

pMp photo-detector was demonstrated with the performance comparable to the state-of-the-art p– π –M–N structure. The optimization strategy witnessed some differences in comparison with the standard photodiodes. The effect of doping in p-contact was investigated to optimize the device performance. By decreasing the p-contact doping level to avoid excessive accumulation of carriers near the junction, the electrical performance was significantly enhanced. High performance and high operating temperature was demonstrated for 4.9 μ m cut-off pMp devices with BLIP temperature of 165 K (Fig. 5).

In addition to using different structures for optimizing bulk performance of MWIR photo-detectors to suppress the dark current density further, suppression of the surface leakage current should be also considered. Below 120 K, the surface leakage current caused by band-bending becomes the dominant mechanism of dark current in photodiode. In order to solve the issue of band-bending at surface of MWIR photodiodes, a passivation of SiO₂ combining with the gating technique was used [9] (Fig. 6-left). The band-bending happening at the sidewall can be controlled actively by applying a voltage to the gate which covers the sidewall of the devices. Further details about gating technique has been presented by Chen et al. [9]. A comparison between MWIR photodiodes dark current density and differential resistance $\times$ area, before and after using gating techniques, is shown in Fig. 6 (right). At 110 K, the dark current of gated device is decreased by more than 2 orders of magnitude, and reaches the measurement system noise floor. With a quantum efficiency of 48%, a 4.7 μ m cut-off

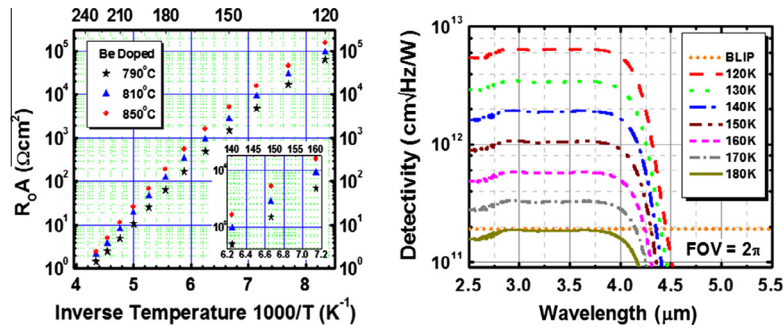


Fig. 4. (left) Comparison of differential resistance area product as function of doping. Doping levels are presented as a function of Beryllium cell's temperature. (right) Calculated detectivity spectrum as function of temperature in comparison with the BLIP line with a 300 K background and 2π field of view.

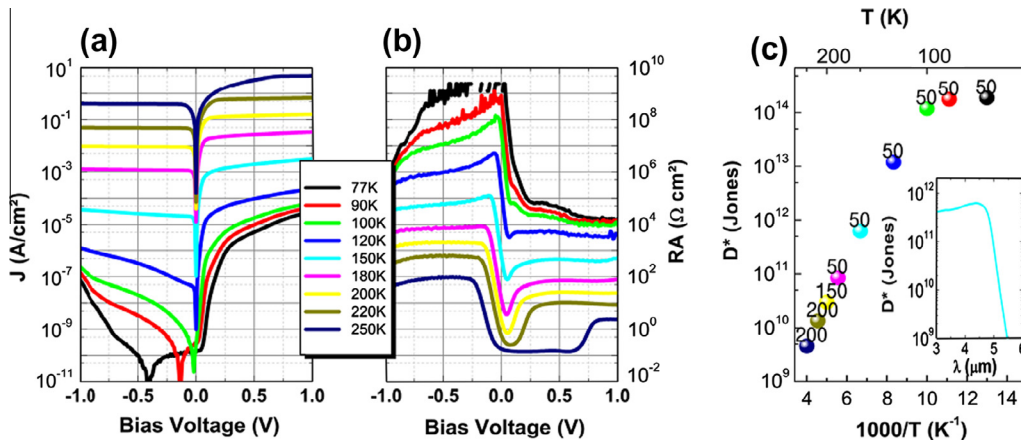


Fig. 5. (left) Temperature dependence of MWIR pMp device dark current density and differential resistance $\times$ area. (right) Temperature dependence of MWIR pMp device specific detectivity (D^*). Label of each point indicates bias (in mV) required to maximize the detectivity. D^* spectrum at 150 K is shown in the inset.

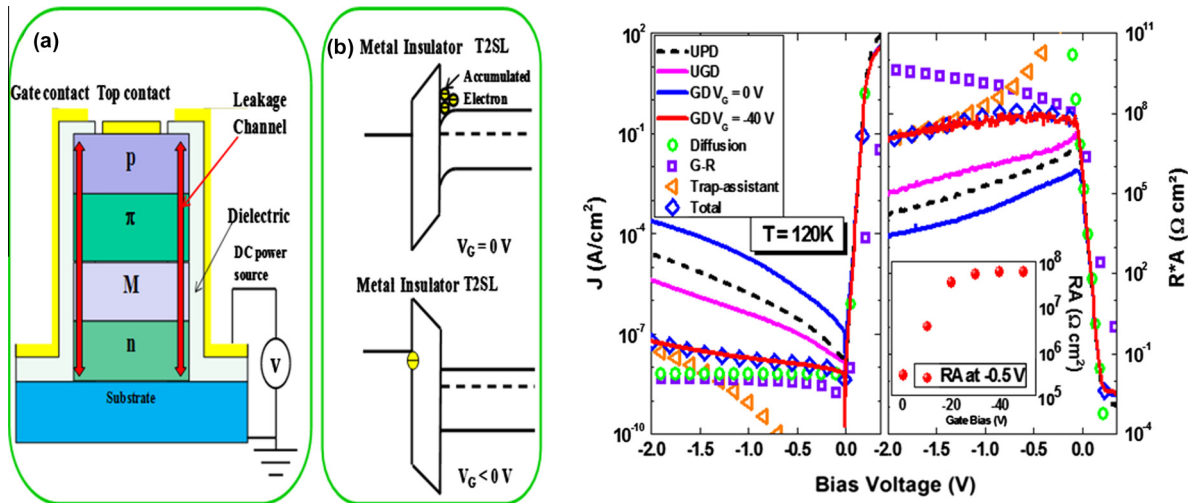


Fig. 6. (Left) Schematic diagram of a gated photodiode (a) and the control of its surface band-bending (b). (Right) Comparison of dark current density and differential resistance $\times$ area of T2SL MWIR photodiode before and after applying gating technique.

device attains a specific detectivity of 2.5×10^{14} Jones at 110 K, which is 3.6 times higher than ungated devices (Fig. 7).

After optimization of the T2SL-based MWIR device performance, the device can be used for fabrication of FPA. In order to fabricate MWIR T2SL FPA, some modifications were made on devices structure [7]. The active region design was slightly changed to achieve a cut-off wavelength of $5 \mu\text{m}$ at 150 K. A $1.5 \mu\text{m}$ InAsSb etch-stop layer was grown prior to the photodiode growth to aid

substrate removal. The MWIR FPA was hybridized to an Indigo ISC9705 ROIC. The FPA was mounted on a leadless ceramic chip carrier (LCCC) and loaded in a liquid nitrogen cooled cryostat and tested with a CamIRA infrared FPA testing system from SE-IR Corporation. FPA was evaluated at operating temperatures ranging from 81 to 150 K with a frame-rate of 30 Hz.

Radiometric characterization of MWIR FPA resulted in median Noise Equivalent Temperature Differences (NETDs) of 14 mK

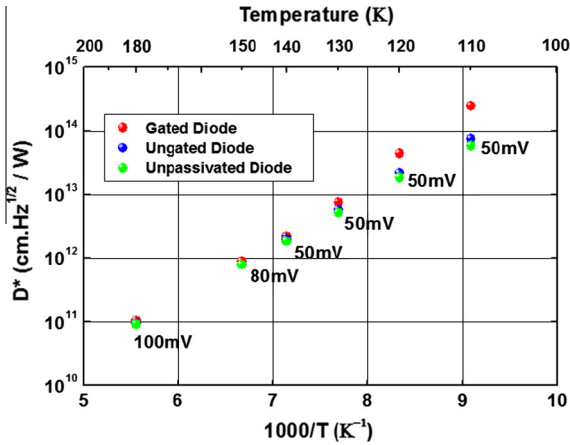


Fig. 7. Specific detectivity of unpassivated diode, ungated diode, and gated T2SL MWIR photodiode at saturation gate bias at different operating temperatures. Labels indicate the bias values (in mV) required to maximize the detectivity.

(5 ms) and 8 mK (12 ms) using a Janos MWIR lens with a F# of 2.3. Fig. 8 (left) shows the NETD histograms for both 5 and 12 ms integration times at 81 K in logarithmic scale. The absence of tails in the histograms is indicative of high operability. The measurement resulted in 98.9% operability, defined by the pixels below 2 times the NETD median value [10]. The median NETD remains constant below 120 K as it is shown in Fig. 8 (right). The rise in median NETD at operating temperatures above 120 K is caused by rising dark current density and the shortened integration time to prevent ROIC sampling capacitor saturation [11].

Human body imaging at different operating temperatures ranging from 86 to 170 K is demonstrated in Fig. 9 [11] (a 2-point non-uniformity correction was applied). Based on the measured NETD values at different temperatures (Fig. 8-right), the imaging quality expected to stay unchanged up to 120 K.

2.3. Long-wavelength infrared photo-detectors and focal plane arrays

Going toward longer detection wavelength, the energy gap gets smaller and the material therefore becomes more sensitive not only to the bulk properties but also to the surface states of the exposed sidewall. The challenge for long-wavelength infrared (LWIR) photo-detectors is to decrease the bulk dark current as well as the leakage current at the sidewalls of the devices simultaneously.

In order to demonstrate LWIR T2SL-based photo-detectors, a superlattice design of 13 mono-layers (MLs) InAs and 7 MLs GaSb

with forced InSb interfaces was chosen for a desired cut-off wavelength around 11–12 μm . The growth schedule for LWIR device consists of a 0.5 μm thick GaSb p+ buffer layer, followed by a 0.5 μm thick p-doped (Be doped) superlattice region, a slightly p-doped superlattice layer as absorption region, a 0.5 μm thick n-doped (Si doped) region and finished with a thin InAs n-doped (Si) contact. Structural characterization with high resolution X-ray diffraction (HRXRD) exhibited high order diffraction satellites and a lattice mismatch to GaSb substrate of less than 500 ppm. Measurement with an atomic force microscope (AFM) showed morphology with long atomic steps and a root-mean-square (RMS) roughness of under 1.5 Å over an area of $20 \times 20 \mu\text{m}^2$. Using this superlattice structure, It was demonstrated that it is possible to increase the quantum efficiency of the devices by growing thicker active regions. Devices with 6 μm active region presented a quantum efficiency averaging at 54% [12].

In order to optimize the electrical performance of LWIR device, active region should be doped which resulted in almost one order of magnitude of improvement. However, increasing the doping level in active region causes strong band-to-band tunneling (BTB) and increases the dark current density. To suppress BTB current, the M-structure superlattice barrier was inserted between the standard i and n-regions. This layer has been shown to efficiently reduce the built-in electric field and improve the R_0A by one order of magnitude [13].

As the performance of bulk material and structural design are improved, the surface leakage becomes important and needs to be reduced. Surface leakage current is believed to originate from abrupt termination of the periodic crystalline structure, contamination from processing, and fixed charges within the passivation layer, which can generate a band-bending on mesa's sidewalls. This band-bending causes electron accumulation or type inversion at sidewall surfaces, resulting in a conduction channel along sidewalls [14] (Fig. 6-left). The etching techniques to delineate device mesas were intensively studied. It turned out that the damage at the device sidewalls due to plasma dry etching severely affected the device performance. Developing a new etching recipe using the Oxford Plasmalab Inductively Coupled Plasma (ICP) system resulted in much smoother sidewalls and better verticality compare to the conventional dry etching method using Electron Cyclotron Resonance (ECR) or combination of dry and chemical wet etching.

In addition to optimization of etching process, an efficient passivation technique should be used to maximize the device performance. SiO_2 is used for passivation of MWIR T2SL photo-detectors but it has been reported to be inefficient in the LWIR because of the smaller band gap of the superlattice. In order to address this issue, a double hetero-structure design was proposed with the utilization

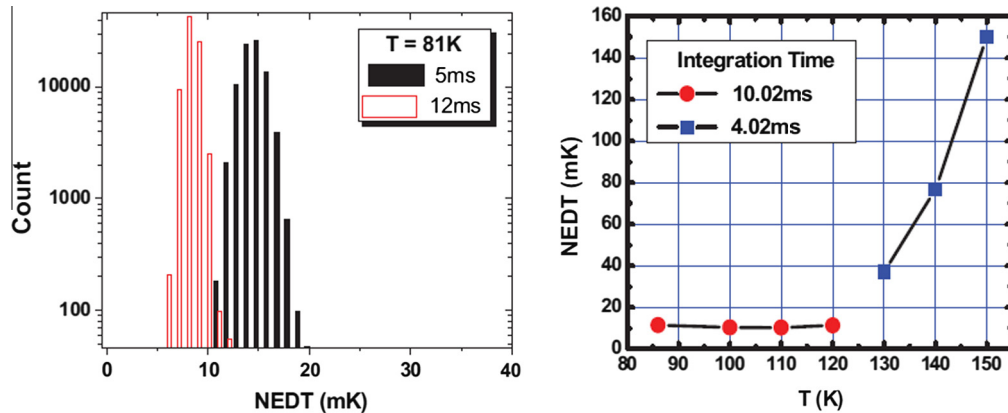


Fig. 8. (left) NETD histogram of MWIR T2SL FPA for 5 and 12 ms integration times at 81 K. (Right) MWIR T2SL FPA NETD evolution with operating temperature. Integration time was reduced above 120 K to avoid ROIC sampling capacitor saturation.



Fig. 9. Human body imaging, using 2-point non-uniformity correction, is demonstrated at different operating temperatures ranging from 86 to 170 K.

of two MWIR superlattice contact regions [14]. The higher bandgap of the contacts prevents the charge inversion of carriers at the device sidewall, thus reducing the surface leakage channel. This design has shown the viability of the device with both SiO_2 and polyimide passivation. The schematic diagram of a device design that combines both high optical and high electrical performance is shown in Fig. 10. A strong optical response and a high quantum efficiency ($>50\%$) were obtained thanks to a long absorption path and high material quality. M-structure and the double hetero-structure design helped to reduce both bulk dark current and surface leakage current. The device exhibited a dark current level below $5 \times 10^{-5} \text{ A/cm}^2$ at 50 mV reverse bias and a surface resistivity $\sim 40 \text{ k}\Omega \text{ cm}^2$ at 77 K. However, this value is not yet the true performance of the material. Using the ICP etching technique, the same material exhibited almost one order of magnitude decrease of the dark current. Fig. 11 presents the dark current density of the devices processed with ICP, and passivated with different techniques. It appears that the combination of ICP etching and polyimide passivation provide the best electrical performance [15]. However, the discrepancy between different sized diodes indicates that the device performance is still limited by the surface leakage.

In addition to study of effect of double hetero-structure on surface leakage in SiO_2 passivated samples, the effect of doping was also studied. It has been found that a portion of surface leakage current is caused by the direct contact between the SiO_2 passivation layer and the highly doped active region sidewalls [16]. Thus, the passivation layer should be in contact only with sidewalls of low-doped area. Such a requirement can be satisfied without increasing the minority carrier concentration of the active region. A design containing a low-doped buffer layer combined with shallow etching that stops right below the junction level has been practically implemented. In this study SiO_2 passivated single detectors with $10.5 \mu\text{m}$ cut-off wavelength, quantum efficiency of 15.5% at

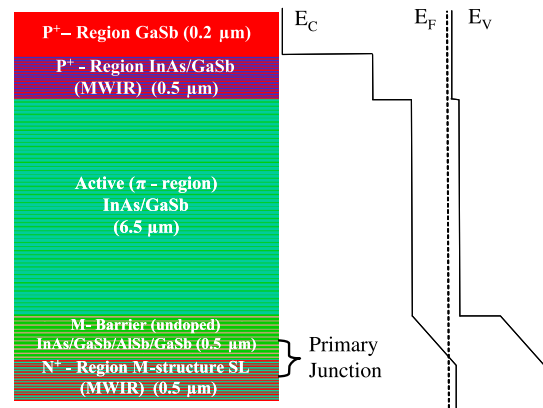


Fig. 10. The device structure and band diagram of a p- π -M-n superlattice photodiode. While the thicker active region increases optical efficiency, the M-barrier and double hetero-structure effectively blocks dark current and limits surface leakage.

zero bias, exhibited a dark current level of $3.5 \times 10^{-5} \text{ A/cm}^2$ at 50 mV reverse bias and a RA_{max} of $6000 \Omega \text{ cm}^2$ at 77 K. Fig. 12 shows that the dark current at reverse bias is reduced by up to two orders of magnitude with respect to the dark current in the usual devices.

Based on the high quality and high uniformity LWIR photodiodes, a high performance megapixel $1 \text{ K} \times 1 \text{ K}$ LWIR T2SL FPA was successfully demonstrated [17]. The fabrication began with the deposition of Ti/Pt/Au/Ti top contacts using electron-beam metal evaporation on the material described above. A dielectric hard mask was deposited using plasma enhanced chemical vapor deposition (PECVD) followed by hard mask definition using electron cyclotron resonance-reactive ion etching (ECR). The mesas were

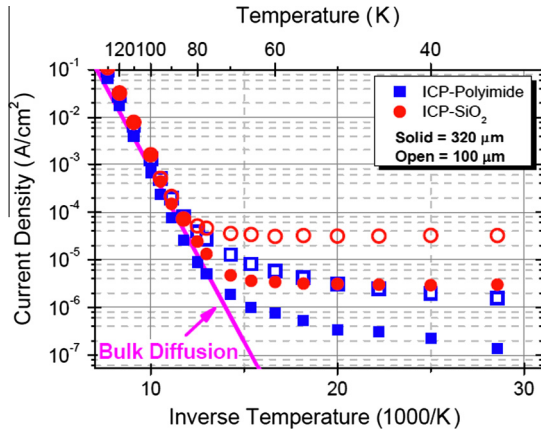


Fig. 11. Temperature dependent dark current density measurements of 320 μm (solid data point) and 100 μm (open data point) diameter diodes for samples with different passivations are shown at 50 mV reverse bias.

then defined using inductively coupled plasma (ICP) etching. ICP etching conditions were optimized for narrow trenches resulting in a detection area of $\sim 231 \mu\text{m}^2$ per pixel. After this step, sample was cleaned and passivated with SiO_2 using PECVD. Top and bottom window openings were formed to allow electrical access to the pixels and ground ring, and the Ti/Pt/Au bottom contact was deposited. This was followed by indium bump deposition on the FPA and the ROIC. Then, the FPA was hybridized to an Indigo ISC0404 readout integrated circuit (ROIC) and under-filled with a low viscosity epoxy. After under-filling the hybrid, the last step was removing the 625- μm -thick GaSb substrate to increase the FPA's external quantum efficiency; Finally, the substrate was removed completely by a combination of mechanical and chemical processes [18].

The preliminary imaging results at 81 K and 68 K, with 2-point uniformity correction applied, are shown in Fig. 13. The noise equivalent temperature differences (NETDs) were measured with 20 °C and 30 °C backgrounds, an integration time of 0.13 ms, an F/2 large-format lens from StingRay Optics and a frame rate of 15 Hz. At a reverse bias of ~ 25 mV, we obtained a median NETD value of 27 mK and 19 mK at 81 K and 68 K, respectively. Fig. 14 shows the NETD histograms for both temperatures. This FPA demonstrated quantum efficiency operability of 95.8% and 97.4% at operating temperatures of 81 K and 68 K, respectively [18,19].

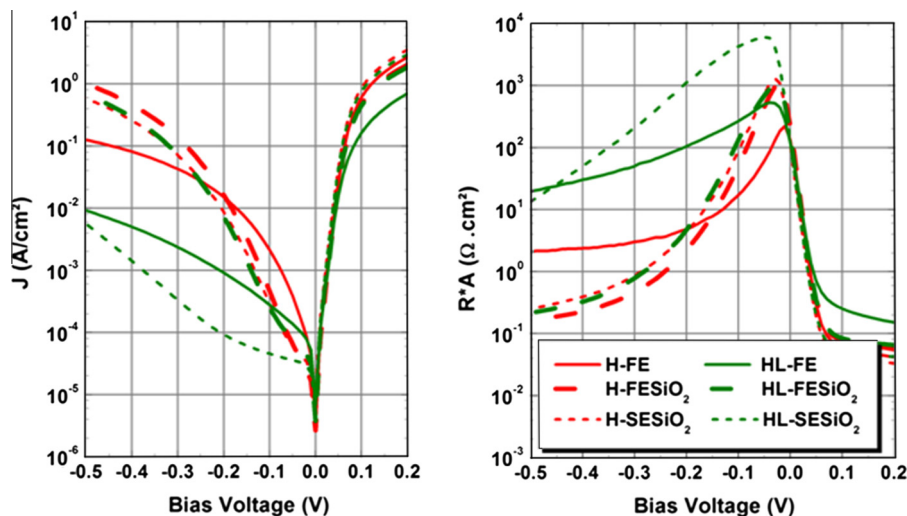


Fig. 12. Comparison of electrical performance of LWIR samples with heavy doping and light doping with different etching-depths.

2.4. Very long-wavelength infrared photo-detectors

T2SL can cover VLWIR detection regime up to 32 μm simply with adjusting InAs and GaSb layers thickness. In this regime, T2SL has a great potential to outperform MCT photo-detectors thanks to its great uniformity and higher electron effective mass that can reduce the tunneling current. A p- π -M-n design was used for VLWIR device with a cut-off wavelength around 14 μm . The superlattice is composed of 16 MLs InAs and 9 MLs of GaSb, with a nominal band-gap of 80 meV. However, the same M-structure used in the LWIR design appears to have a higher conduction band than the VLWIR design. As a consequence, the photo generated electron at the π -region could not get to the n-region to contribute to the photocurrent. In order to improve the quantum efficiency of the device, different techniques have been developed to suppress the effect of the barrier in the conduction band while keeping the same barrier in the valence band. The first method is modifying M-structure design which results in absolutely zero band-discontinuity between M-structure and T2SL-based active region. Another method is to keep the M-structure design that have the highest effective mass, and adjust the doping level of the barrier such that the barrier width is significantly reduced [20,21] and allows photo-generated carriers to be extracted successfully. As a consequence, a compromise between optical and electrical performance was obtained. The specific detectivity attains $\sim 4 \times 10^{10}$ Jones at 77 K indicating the Background Limited Performance (BLIP) of the device with a 300 K background and 2π field of view. This performance, without passivation protection and without anti-reflection coating for the enhancement of the optical efficiency, is equivalent to the best reported value for the state-of-the-art MCT at this wavelength.

3. High performance LWIR and MWIR photo-detectors and FPAs on GaAs substrate

In previous sections, we discussed about growing different types of T2SL-based photo-detector on GaSb substrate. However, growing on GaAs substrate can decrease fabrication cost for Type-II superlattice-based imagers. In order to grow high quality superlattices on a GaAs substrate, a defect free buffer layer should be grown by reducing strain and the number of dislocations/spiral mounds that could occur with the $\sim 7\%$ lattice mismatch between Type-II superlattices and GaAs substrate. This buffer can be a GaSb for N-on-P photodiode structure of a combination of GaSb and InAsSb for P-on-N ones. Both of these two buffers are nearly lattice



Fig. 13. Images of a student taken with the $1\text{ K} \times 1\text{ K}$ FPA at 81 K (left) and 68 K (right).

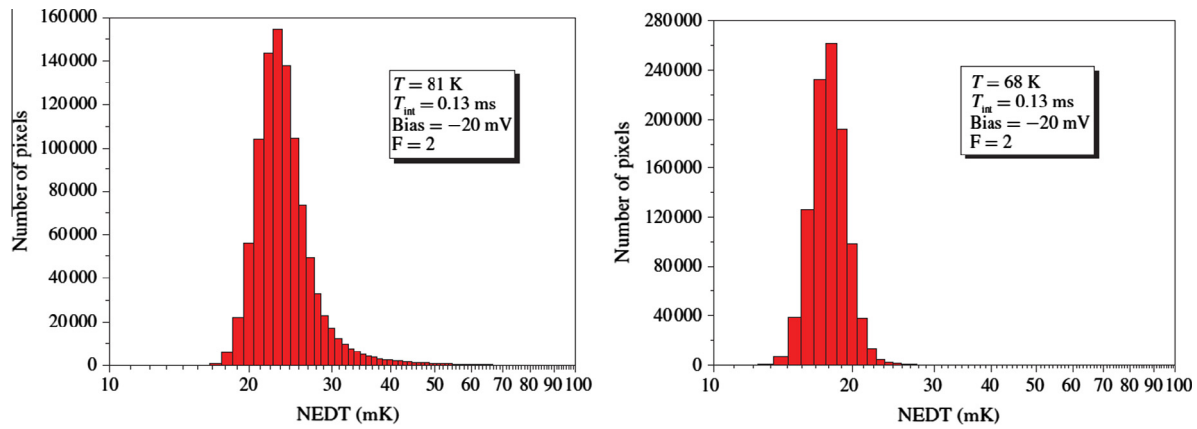


Fig. 14. $1\text{ K} \times 1\text{ K}$ FPA NETD histograms at 81 K (left) and 68 K (right).

matched to the superlattice by design. When these buffer layers are directly nucleated and grown on GaAs, the resulting material is rough due to strain relaxation or form threading dislocations that continues during superlattice growth. They can act as trap centers and enhance the non-radiative recombination processes or create conductive leakage channels inside the photodiode which would cause severe degradation to diode performance. In order to decrease this effect, we need to grow a smooth GaAs buffer layer to reduce the roughness of the substrate after the removal of oxide layers. Then, we need to nucleate a thin GaSb film on GaAs to initialize the crystal plane and reduce the dislocation seed density. Finally, a GaSb recovery layer should be grown to smooth out the surface and to absorb the lattice mismatched strain [22]. For each stage, the growth conditions such as growth temperature, growth rate, III/V ratio as well as layer thickness needs to be optimized for good overall surface morphology of the final layer.

We use a Gen-II Intevac Solid Source Molecular Beam Epitaxy (MBE) equipped with group III SUMO cells and group V valved crackers. A 2" n-doped GaAs wafer was loaded for the growth of GaSb on GaAs. After the deposition of a $\sim 0.2\text{ }\mu\text{m}$ GaAs buffer layer, the GaSb layer was nucleated using the low-temperature nucleation technique [23], followed by a 4 μm thick recovering GaSb layer. The altered kinetics of lattice relaxation at low temperature will reduce threading dislocation density. The roughness of the relaxed layers will then be recovered by higher temperature growth mode, resulting in higher crystal quality, lower defect density, and lower roughness surfaces RMS value. After growing the buffer layer, MWIR and LWIR photodiodes were grown [22,24].

The MWIR superlattice design consisted of 7 and 11 MLs of InAs and GaSb (per each period), respectively. It was aimed to have a cut-off wavelength of $3.98\text{ }\mu\text{m}$ at 77 K. The device homo-junction p- π -n structure had a 500 nm p-type ($p \sim 1 \times 10^{18}\text{ cm}^{-3}$) region, a 2 μm non-intentionally doped region, and a 500 nm n-type ($n \sim 1 \times 10^{18}\text{ cm}^{-3}$) region. The growth was finished by a 100 Å n^+ InAs capping layer. The LWIR hetero-junction p- π -M-n photodiode had the same thicknesses for each layer as the MWIR photodiode, except an additional 500 nm M-barrier. The LWIR superlattice design, with and aimed cut-off wavelength of $\sim 11\text{ }\mu\text{m}$, for active region had 13 and 7 MLs of InAs and GaSb in each period, respectively. For p- and n-regions two superlattices with cut-off wavelengths of ~ 5 and $\sim 6\text{ }\mu\text{m}$ were used.

After material growth, the MWIR sample was processed into single element (SE) detectors with linear sizes ranging from 100 to 400 μm . A mixture of BCl_3 :Ar dry etching and citric acid-based wet etching solution was used to define the mesas. Both Ti/Pt/Au top and bottom metal contacts were formed using electron-beam deposition technique. The sample was not passivated, but a thorough solvent-based cleaning was applied after each major step to ensure clean sidewalls [24].

Fig. 15 (left) shows the current-voltage and differential resistance $\times$ area characteristics of the device as a function of temperature. The dark current density was $\sim 6 \times 10^{-5}\text{ A/cm}^2$, corresponding to a differential resistance $\times$ area of $1600\text{ }\Omega\text{ cm}^2$ at zero bias [24]. The quantum efficiency of the device as a function of wavelength at different operating temperatures is shown in the right side of Fig. 4. By increasing the operating temperature, the

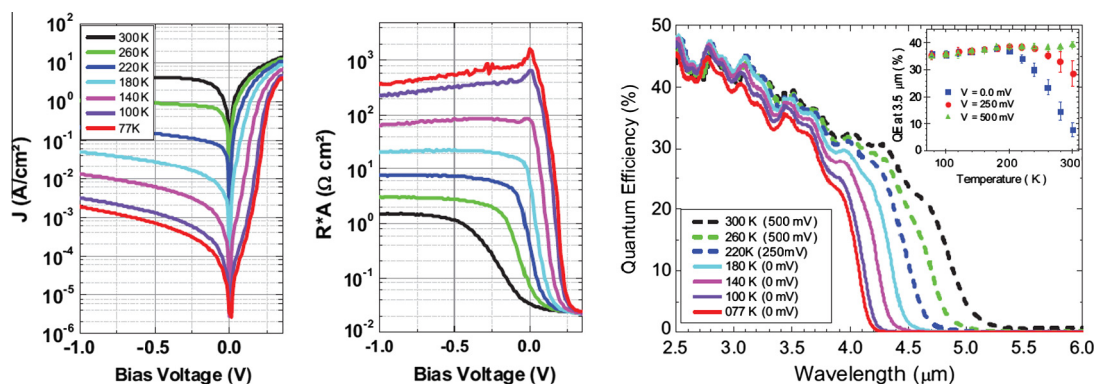


Fig. 15. (left) Dark current density and differential resistance $\times$ area characteristics of the sample as a function of temperature. (right) Quantum efficiency spectrums of the device at different operating temperatures. The inset is the temperature dependent quantum efficiency at 3.5 μm at different reverse bias.

cut-off wavelength of the device varies from 4.04 to 4.8 μm . The quantum efficiency at 3.5 μm is 36.4% at operating temperatures below 200 K. At operating temperatures above 200 K, the quantum efficiency at zero bias slowly decreases. However, it could be recovered to the maximum quantum efficiency by some applied bias as it is shown in Fig. 15 (right). This bias dependency was observed in Type-II superlattices-based devices grown on GaSb substrate as well and is attributed to the decrease of the diffusion length at higher operating temperatures [11]. The oscillatory fringes in quantum efficiency spectrum are due to Fabry–Perot cavity between the superlattice/air interface and the GaAs/GaSb interfaces [18].

After successful demonstration of MWIR Type-II superlattice-based devices on GaAs substrate, an FPA was fabricated based on this material which followed similar steps as described before, except for the substrate removal step. The FPA was hybridized to an Indigo ISC9705 ROIC. A chemical procedure was used to fully remove the GaAs substrate [25]. Subsequently, the FPA was mounted on a leadless ceramic chip carrier (LCCC) and loaded in a liquid nitrogen cryostat and tested with a CamIRa infrared FPA evaluation system from SE-IR Corporation at 67 K. The imaging and tests were performed at a frame rate of 30 Hz and a reverse bias of 14.4 mV, respectively. An integration time of 10.02 ms was selected to accommodate higher frame rate and good dynamic range of the camera. A median noise equivalent temperature difference (NETD) of 13 mK was measured using a 25 mm Janos ASIO MWIR lens with F# of 2.3 (Fig. 16-left). The FPA operability based on NETD measurement was 82.1% (the pixels below two times the median NETD

value). An NETD of 10mK is achievable by increasing integration time to 19.06 ms in order to achieve higher signal-to-noise ratio [25]. This was the first attempt to demonstrate T2SL FPA on GaAs substrate and the FPA performance is expected to improve as the growth and processing of this technology matures. In Fig. 16 (right), the FPA imaging result is shown where a 2-point non-uniformity correction was applied.

After successful demonstration of MWIR photodiode and FPA on GaAs substrate, we tried to demonstrate LWIR photodiode on GaAs substrate. The fabrication process was the same as MWIR one. However, we fabricated and extra die and passivated it with polyamide. Fig. 17 (left) demonstrates the comparison between electrical performance of polyamide-passivated and unpassivated LWIR devices. This comparison indicates that the electrical performance of LWIR photodiodes grown on GaAs substrate is limited by surface leakage up to 500 mV reversed bias [22].

In right section of Fig. 17, a comparison between the optical performances of LWIR T2SL photodiodes grown on GaAs and GaSb substrates is shown. The 50% cut-off for both samples is at 11 μm . The slight higher quantum efficiency of photodiode on GaAs can be addressed by Fabry–Perot oscillations. This comparison between Johnson and shot noise detectivity (D^*) of both devices at 77 K shows that both of them are above the background limited performance (BLIP) for the whole 8–12 μm optical atmospheric window. We used the definition of BLIP condition as the Johnson noise (Because the T2SL LWIR photodiodes in this study can operate at zero bias and there is no shot noise at zero bias condition.) being equal to the photo-signal for a detector with 100%

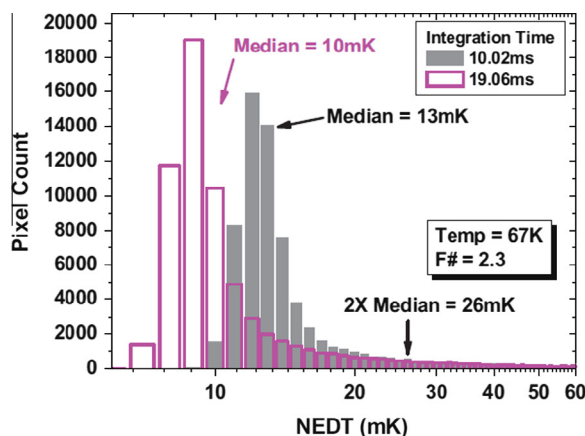


Fig. 16. (left) NETD histogram of the MWIR T2SL FPA on GaAs substrate measured with 10.02 ms and 19.06 ms integration times at 67 K. (right) Imaging of MWIR T2SL FPA on GaAs substrate at 67 K (a 2-point non-uniformity correction was applied).

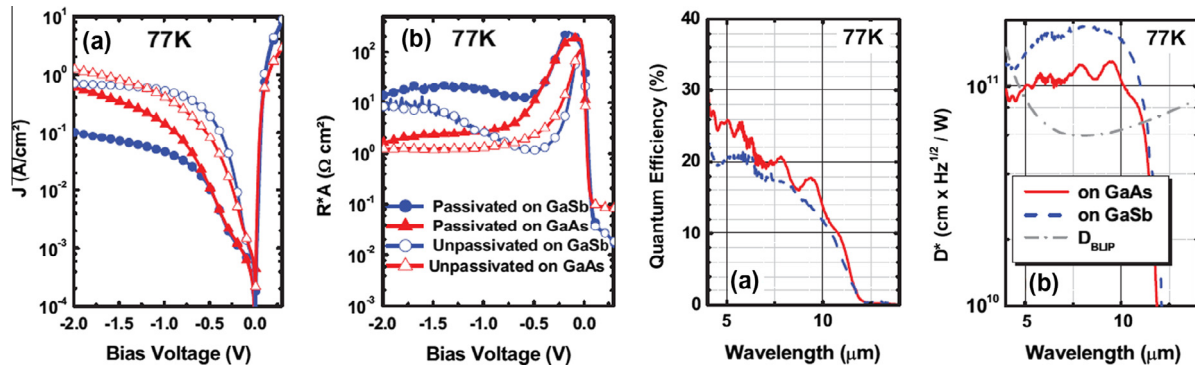


Fig. 17. (left) Comparison of dark current density and differential resistance $\times$ area characteristics of polyamide-passivated and unpassivated LWIR photodiodes on GaAs substrate. (right) Quantum efficiency and specific detectivity of LWIR photodiodes grown on GaAs and GaSb substrates at 77 K in comparison with the BLIP line with a 300 K background and 2π field of view.

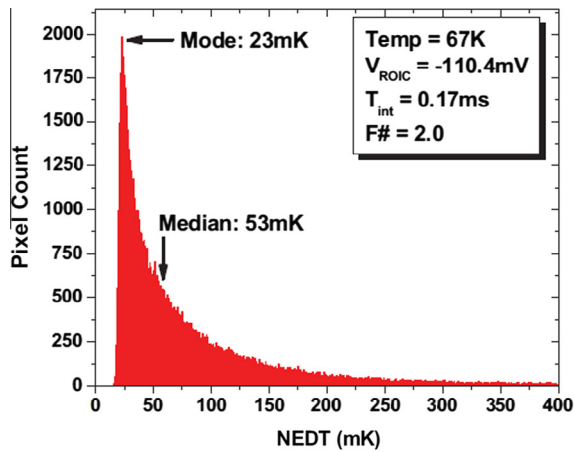


Fig. 18. (left) NETD histogram of the LWIR T2SL FPA on GaAs substrate measured at 67 K. (right) Imaging exhibited using LWIR T2SL FPA on GaAs with a 2-point non-uniformity correction.

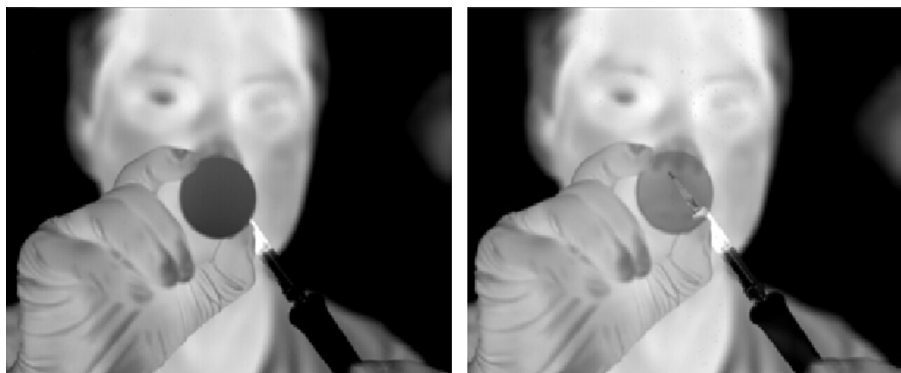


Fig. 19. Dual-band imaging using a 512×640 T2SL FPA with 9.5 μm (left) and 13 μm (right) 100% cut-off wavelengths at 77 K. A narrowband filter centered at 11.3 μm is placed in front of a soldering iron.

quantum efficiency being illuminated by a 300 K blackbody with 2π field of view (FOV). The LWIR device grown on GaAs substrate demonstrated a D^* of 1.1×10^{11} Jones at 77 K.

Subsequent to successful demonstration of the LWIR photodiode on GaAs substrate, an FPA was fabricated from this material using the same procedure described before for MWIR FPA and characterized at 67 K. In order to optimize the performance, a frame-rate of 30 Hz, integration time of 0.17 ms, and a reverse

bias of 110.4 mV were used, respectively. The radiometric characterization produced a median NETD of 53 mK using a Janos LWIR lens with a F# of 2 (Fig. 18-left). Since this work was the first attempt at producing a T2SL FPA on GaAs substrate, the performance is expected to improve as the growth and processing of this technology matures. Imaging of the LWIR imager is demonstrated where a 2-point non-uniformity correction was applied (Fig. 18-right).



Fig. 20. Dual-band imaging using a 256×320 T2SL FPA with $\sim 5 \mu\text{m}$ (left) and $\sim 12 \mu\text{m}$ (right) 100% cut-off wavelengths at 77 K. Lighter's flame has different signatures in different infrared bands.

4. High performance dual-band FPAs

Based on previous experiences in design and fabrication of single-band T2SL photodiodes and FPAs, Center for Quantum Devices has demonstrated different types of dual-band T2SL FPAs in LWIR [26,27] and MWIR regimes. A high performance 512×640 dual-band T2SL FPA has been demonstrated in LWIR regime [27]. The 100% cutoff wavelengths are $9.5 \mu\text{m}$ and $13 \mu\text{m}$ at 77 K. The imaging performance is shown in Fig. 19.

After successful demonstration of LWIR dual-band T2SL FPA, a high performance 256×320 MWIR/LWIR T2SL FPA was demonstrated. The 100% cutoff wavelengths are $\sim 5 \mu\text{m}$ and $\sim 12 \mu\text{m}$ at 77 K. Details regarding this work will be elaborated in a future publication. Fig. 20 shows the imaging quality of this FPA. As it is shown, the flame has different signatures in MWIR and LWIR bands.

5. Conclusions

We presented a summary of the recent progress towards T2SL-based photo-detectors and focal plane arrays for infrared detection at different regimes (SWIR, MWIR, LWIR, and VLWIR). T2SL has demonstrated itself as a very attractive quantum low-dimensional system with theoretical limits that have not been reached yet. The review of the work on high operating temperature, megapixel, alternative substrate, and multispectral FPAs demonstrates that this material system is making firm steps toward the era of infrared imaging and can be considered as a strong candidate for replacing the current state-of-the-art material systems for infrared imaging.

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